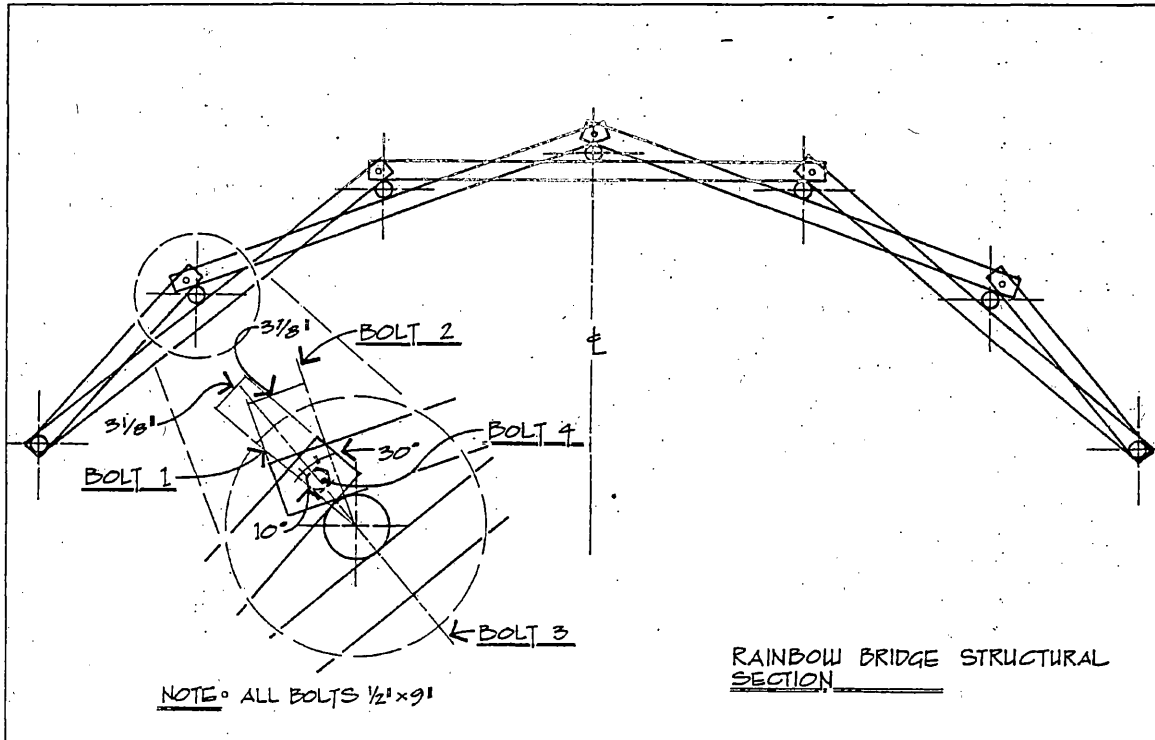


Innovative Structural Applications for Small  
Roundwood: Interlaced Arch Bridge

01-JV-11221615-105

01-105  
Final Draft  
01-JV-11221615-105

## Innovative Structural Applications for Small Roundwood: Interlaced Arch Bridge



Submitted By

Stephen P. Mead Ph.D.  
Department of Construction Management  
College of Engineering  
Northern Arizona University

Submitted To:

United States Department of Agriculture  
Forest Service  
Rocky Mountain Research Station  
240 West Prospect Road  
Fort Collins, Colorado 80526-2098

**DRAFT**

Forest Service Agreement No. 01-JV11221615-105  
Cooperator Agreement No. EGR 346 M

ROCKY MOUNTAIN RESEARCH STATION LIBRARY  
FORT COLLINS CENTER  
240 W PROSPECT RD  
FORT COLLINS, CO 80526-2098

## Table of Contents

Description	Page
Abstract.....	1
Introduction.....	2
Objectives of the Study.....	2
Prototype Development.....	2
Model Development.....	2
Developing the Prototype.....	4
Materials Used.....	5
Rigging Systems.....	5
Constructability Analysis.....	6
Economic Analysis.....	7
Other Potential Uses.....	8
Roof Structures.....	8
Other Arch Structures.....	9
Engineering Analysis.....	10
Finite Element Analysis.....	11
Analysis of Test Models.....	11
Finite Element Analysis.....	12
Strength and Serviceability Analysis.....	13
ASD Analysis.....	13
Connection Analysis.....	14
Recommendations For Future Bridge Designs.....	16
Conclusions and Recommendations for Future Work.....	17
Bibliography.....	18

# Innovative Structural Applications for Small Round Wood

## Abstract

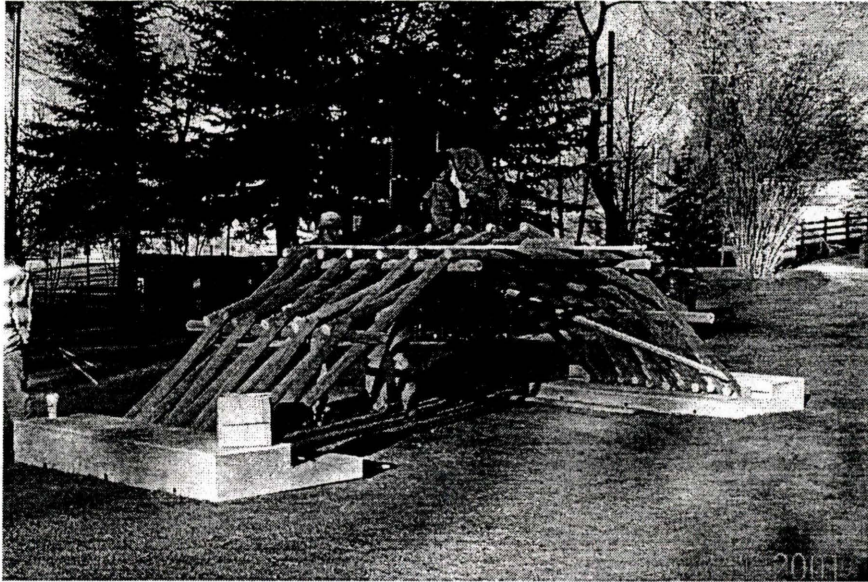
This research project describes the design and construction of an interlaced arch that can be fabricated from small round wood. Invented by the ancient Chinese, this structural system uses a series of interlocking wood arches that can be used to build bridges, roof systems, domes, and storage buildings. This report discusses the history of the structure as well as the building materials and techniques that were used to fabricate a bridge prototype. Additionally, the report discusses the economic potential for similar roundwood structures, and provides an engineering analysis of the roundwood bridge prototype.

## Introduction

This report is a summary of work completed under the title "Innovative Structural Applications for Small Round Wood" for the Rocky Mountain Research Station. Currently, there are over 9 million acres of timberland in the Western United States that consist of small-diameter, densely-stocked timber stands. Unfortunately, there are few productive applications for timber with diameters of less than eight inches. In an effort to reduce forest fire potential and to promote forest health, there has been increased interest in how small diameter roundwood can be harvested and utilized. As such, one of the broad objectives of this study was to develop new uses for the wood products that result from forest restoration projects.

Specifically, this research looked at how small round wood products can be used to construct interlaced arch trusses. These unique trusses can be used for several purposes including pedestrian bridges, roof truss systems, and storage buildings. The primary focus of this study was the development of a bridge prototype that uses a system of interlaced wood arches. In a famous twelfth century scroll painting entitled "Ching Ming Festival on the River", a wooden arch bridge is depicted amid a market scene on a riverside. This bridge, called the Rainbow Bridge, uses a unique structural system of segmented log arches that are woven together like a basket. Here, structurally unstable arches are interlaced with each other to form one stable structure. This unique structural system disappeared from use around 1600, but was recently re-discovered by a Chinese engineer, and featured on the NOVA television special "The Secrets of the Lost Empire" (NOVA, 2000).

The prototype developed for this project is similar to the Rainbow Bridge. The bridge was constructed of small roundwood segments that are 3 inches in diameter and approximately 7 feet long. When assembled the bridge structure has an effective span of 18 feet and a height of 6 feet. The prototype was designed and constructed by the Department of Construction Management at Northern Arizona University as part of a class project in commercial building techniques in the Spring of 2001. The project team included students and faculty from the Department of Construction Management as well as structural engineering students from the School of Engineering at Northern Arizona University. Additionally, the project utilized the expertise of Alex Rong, chief engineer for the Delaware River Port Authority and an expert on Chinese bridges. The finished prototype was erected for the 2001 Forest Festival in Flagstaff, Arizona.



**Figure 1.1 Rainbow Bridge Prototype**

## **Objectives of the Study**

The primary goal for this project was to demonstrate and research practical applications for small roundwood products. Within this broad scope of work, there were several specific objectives:

- Construct a full scale prototype of an interlaced round wood arch bridge
- Perform a feasibility analysis of the prototype that will help refine design and connection details, and establish basic costs for labor, material, and equipment
- Perform a basic engineering study of the prototype that can be used to improve the understanding of interlaced round wood structures
- To showcase small diameter wood possibilities at the Flagstaff Forest Festival
- To develop promotional materials that can help demonstrate innovative uses of small diameter wood products

## **Prototype Development**

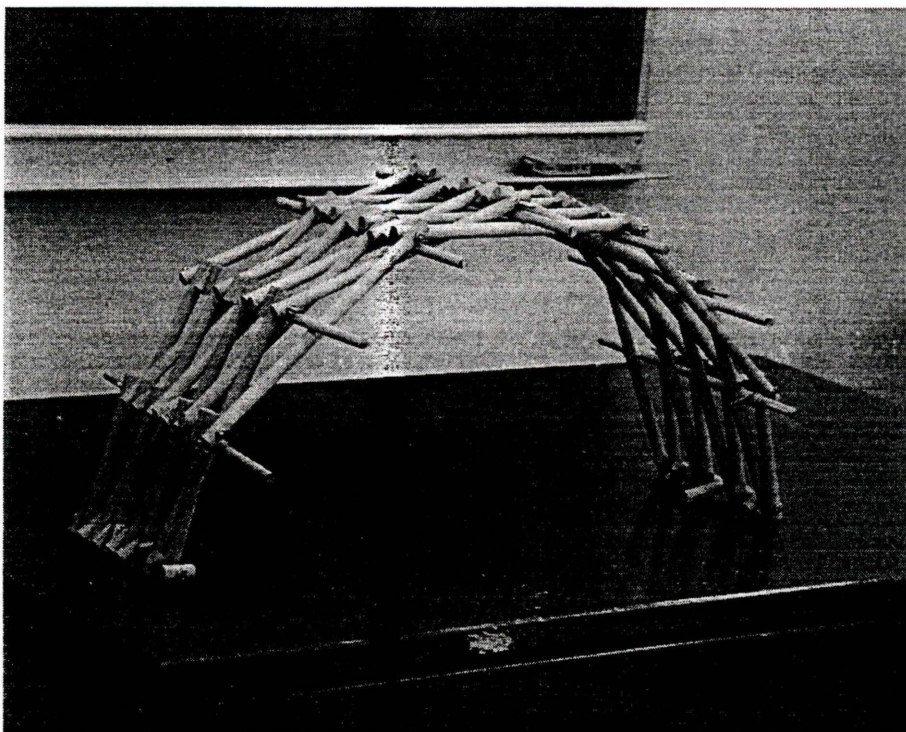
### ***Model Development***

The interlaced round wood arch bridge uses two different types of arches. One arch is composed of three segments, while the other arch uses four segments. These two types of arches are placed next to each other, and then woven together with cross beams for support. The arch pairs can be placed directly adjacent to each other, or spaced at uniform distances to create assemblies of varied widths. The Rainbow Bridge

developed for the Nova project was 50 foot long, and 12 foot wide. This project used five arch pairs to achieve a 20 foot length and six foot width.

The first step in the development of the bridge prototype was the development of several small-scale models. After watching the NOVA video on the "Secrets of the Lost Empires", construction management students were asked to brainstorm ideas on how the structural system could be adapted to the use of small diameter round wood logs. Students were broken into groups and asked to develop ideas for different parts of the bridge including the structural abutments, hinge connections, railing details, and decking supports. Working with Alex Rong, the Chinese Bridge specialist, four small-scale bridge models were designed on paper.

The four design models were then constructed using small diameter dowels and 1/8 th inch all-thread. The models used different arch configurations, arch spans, and arch heights. Once the models were completed, the construction students were asked to dis-assemble and re-assemble each prototype to develop an understanding of the erection and connection requirements for each prototype. These findings were documented in class journals.



**Figure 1.2 Bridge Model**

The completed models were load tested to help determine their structural characteristics. Using a Tinius Olsen load testing machine, the bridge models were subjected to increased point loads until the structures failed.

These tests revealed two flaws in the bridge prototypes. First, the intersection of arches and transverse members needed to be pinned together to prevent lateral movement in the structure. Secondly, the hinge connection needed to be modified to allow for easy construction of the bridge in the field. The original models used a continuous hinges (represented by the all thread) to bind each of the arch segments together. The modeling process showed that this detail would be problematic once the project moved to the prototype stage. Moreover, the modeling process revealed that the horizontal members at the top of the

three sided arches would fail in bending. This mode of failure was later validated through computer modeling of the structure.



**Figure 1.3 Failure of Horizontal Bridge Segments**

### ***Developing the Full Scale Prototype***

One of the specific goals of the project was to make the bridge a modular structure that could be easily assembled in remote locations by people with few skills. For this reason, the bridge was pre-manufactured in our construction laboratories. To give the students a better understanding of how teams are used to construct projects, the class was broken into six groups with specific responsibilities. Each group was asked to complete a project execution plan that included tasks required, labor assignments, tools required, scheduling considerations, and information needed to complete their part of the project. The groups included:

Layout and Coordination - Responsible for overall project management of the project including layout, shop drawings, as - built drawings, marketing materials and cost summaries

Procurement - Responsible for developing material lists and procuring all materials, tools and equipment associated with the project.

Rigging and Safety - Responsible for all aspects of safety for the project including personal protective equipment, scaffolding, crane set up, scheduling, and public safety. Additionally, this group was responsible for developing lifting and rigging devices that were used to place the pre-fabricated bridge assemblies.

Erection - Responsible for the cutting the logs to the proper lengths, drilling connection holes, and fabricating the bridge components.

De-construction - Responsible for dismantling the bridge, organizing and packaging the components for future use, and transporting the materials to future locations.

## Materials Used

**Logs** - For proper connections, the interlaced arch bridge requires round wood of a constant diameter. The procurement team contacted several local vendors and Forest Service personnel to locate a suitable source of round wood for the project. Unfortunately, the wood available would have to be de-barked and milled to meet the constant log diameters required for the prototype and no local mill was available to complete the work. To meet the tight schedule, the project team decided to use pressure treated fence rails from a local lumberyard. The rails measured eight foot long and 3.25 inches in diameter, and fifty rails were required to complete the project.

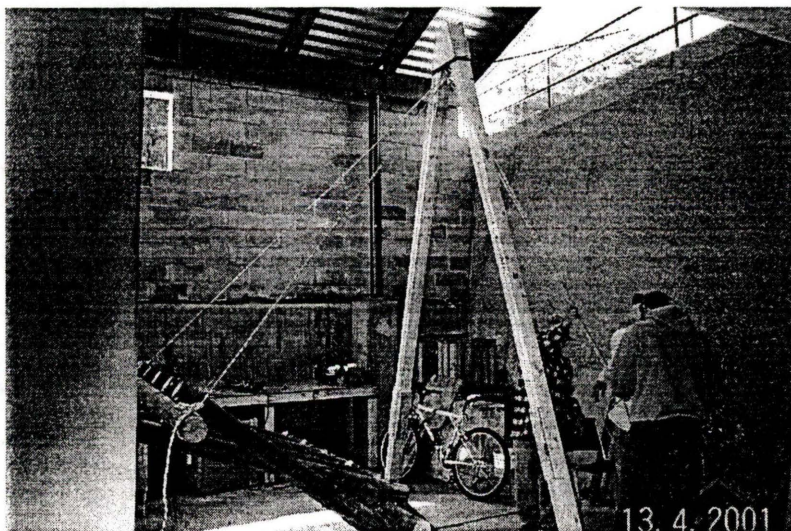
**Bolts** - To connect the bridge segments to the cross members, the team used 1/2" mild steel bolts with nuts and washers. Because the bridge would require dis-assembly, we decided that bolts would provide the most practical connection method. After the members were placed on layout marks, a 5/8" electrician's auger bit was used to drill holes for the bolts in each of the members. The bolts were inserted in the holes and bolts were tightened to approximately 25 ft / lbs.

**Abutments** - Structural arches exert substantial lateral and vertical loads that must be resisted by solid foundations. The design of these foundations is dependent upon the loads imposed, local soil characteristics, and the hydraulics of local streams. After consultation with the design engineer, two stepped concrete footings were constructed for the bridge prototype. The footings were poured with 3000 psi concrete and two mats of #5 steel reinforcing. Additionally, sleeves were cast into the abutments to provide a method for lifting and transporting the foundations to the Forest Festival Site.

**Tool Requirements** - The interlaced arch requires only a few simple tools for assembly. Our construction team used a commercial grade miter saw to cut log members to length, a heavy duty drill to bore holes for connection bolts, and small hand sledges for aligning individual members.

## Rigging Systems

To facilitate erection of the bridge in remote location, the construction team devised a rigging system to erect the prefabricated bridge components safely and efficiently. The rigging system uses two stiff leg derricks to position the bridge halves. A derrick is a simple lifting engine that uses two supporting poles to form an inverted triangle. The triangle is positioned above the piece, and a rope is strung through a sheave that is hung from the apex of the triangle. Once the bridge is connected to the derrick, ropes can be used to raise the structure into place.



**Figure 1.4**      **Gin Pole Rigging System**

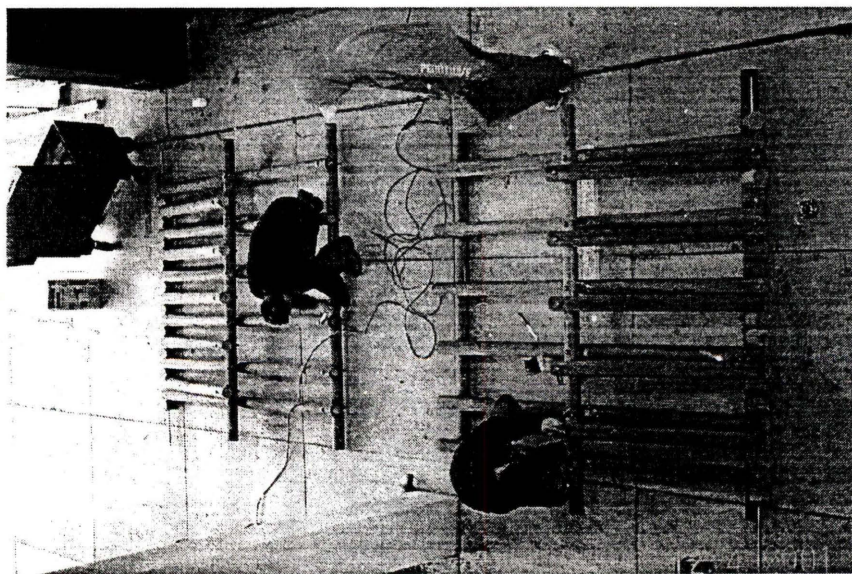
While the derrick system worked adequately in erecting the prototype, there were some problems. Our nylon lifting rope stretched under the load of the bridge segment, making it hard to position the bridge. Additionally, it took substantial force to lift the bridge into place using the rope assemblies. Four students were required for each rope. After reviewing the process, the construction team made several suggestions for improvement. To prevent stretching, the nylon rope should be replaced with a 1/8" steel aircraft cable. To improve the efficiency of the lifting mechanism, the sheave should be replaced with a 4x block and tackle assembly. Finally, a mechanical come-along should be used to ratchet the bridge cable to the desired position.

## ***Constructability Analysis***

Another objective for this project was to develop a constructability analysis for the prototype. Constructability is a process that uses construction and engineering expertise to improve the details, systems, and methods associated with a building structure or assembly. During the development of the prototype, we encountered several problems. After the prototype was erected, the construction teams were asked to conduct a constructability review of the project to increase the efficiency of similar projects. The following is a synopsis of that review.

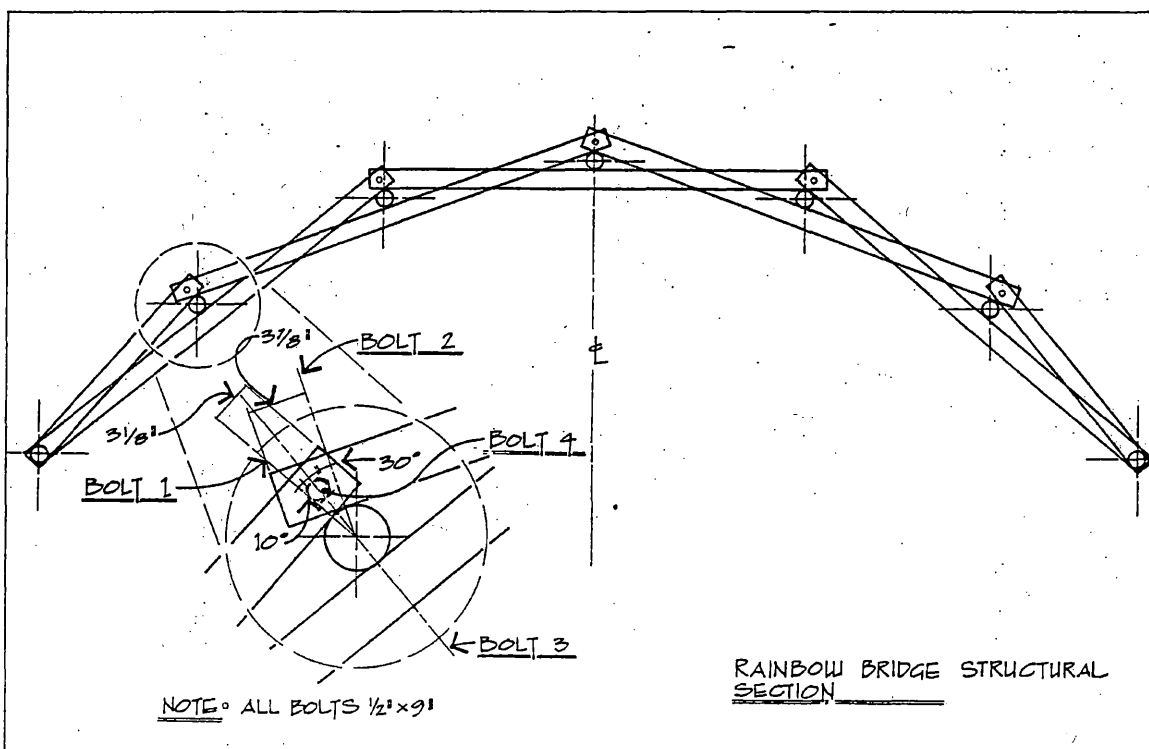
Log Milling Requirements - Given the intricate geometry of the interlaced arch bridge, there can be problems erecting the bridge if the logs are different diameters. Consequently, logs should be milled to a constant diameter. Logs should be straight without significant warps or bows (less than 1/2" in eight feet).

Prefabrication - The geometry of the bridge is tricky. Even after completing detailed shop drawings, the span of our prototype varied by 4" in length from the detailed drawings. Even small variations in the diameter of the logs can change the dimensions of the structure. To minimize cutting and fitting, prefabricate the structure in three sections: two sloping side sections, and a top section. Each section can be laid out on the ground, the pieces positioned, and the holes drilled. The two sloping sections can be adjusted to fit the horizontal middle section of the bridge.



**Figure 1.5      Modular Assembly Technique**

**Connection Details** - The bolt system we devised for this project worked well, however our engineering analysis suggested that the bridge could become much stronger if the segments of each log arch were pinned together. In the original prototype, the arch segments were pinned only to the cross members and not to each other. This problem could also be solved with the use of a steel sleeve. The sleeve could be prefabricated to the proper angle and then the logs could be slid into opposite ends of the sleeve and then attached to the cross members. A three or four inch steel conduit would be a low-cost solution to fabricating the sleeves. Additionally, the sleeves would reduce labor costs associated with fabrication and erection.



**Figure 1.6 Bridge Section and Connection Detail**

**Abutment Details** - Anytime that the end grain of a wood log touches concrete there can be problems. In effect, the end grain of a wood log acts like a box of straws. When placed in contact with the ground or a wet surface, water will wick up the end of the log causing long term dry rot. For this reason, the logs need to be attached to the abutments in a way that will eliminate moisture problems while stabilizing the logs. One elegant solution to this problem is to cast a sloping surface into the abutments that provides adequate support for the logs but also drains water away from the log surfaces. Other solutions use steel spline plates that are cast into the abutments and fitted to the end of each log.

## ***Economic Analysis of Prototype***

In an effort to gauge the actual costs associated with the construction of the prototype, the erection teams developed complete cost summaries for the project. The summaries include all costs associated with the construction of the full scale model, but does not include materials, equipment or labor required for the bridge decking and railings.

Total project material and equipment costs totaled \$1800 or approximately \$15 per square foot. The material costs were approximately \$10 per square foot, while the equipment costs were approximately \$5 per square foot. The materials for decking and rails would add approximately \$5 per square foot to the total costs. Other potential costs include painting and shipping costs.

We should note that the prototype costs would be substantially higher than structures developed with mass manufacturing in mind. We estimate that using pre-manufacturing techniques, economies of scale, and standardized details, material costs could be reduced by up to 50%. Pre-manufacturing would also reduce on-site labor erection costs. While costs would vary according to site and geographical location, pedestrian bridges similar to the prototype, could be manufactured and installed for \$20-25 per square foot; well below the costs of similar pre-manufactured steel or glulam bridges.

Perhaps the greatest advantage of the interlaced bridge design is its portability. Given the details shown here, small diameter roundwood segments can be pre-fabricated and transported on a truck, all terrain vehicle or pack animals to isolated locations. Given the simple connection details, the roundwood logs can be erected with minimum construction skills, making the structure useful for remote hiking trails, forest service roads, and shelters.

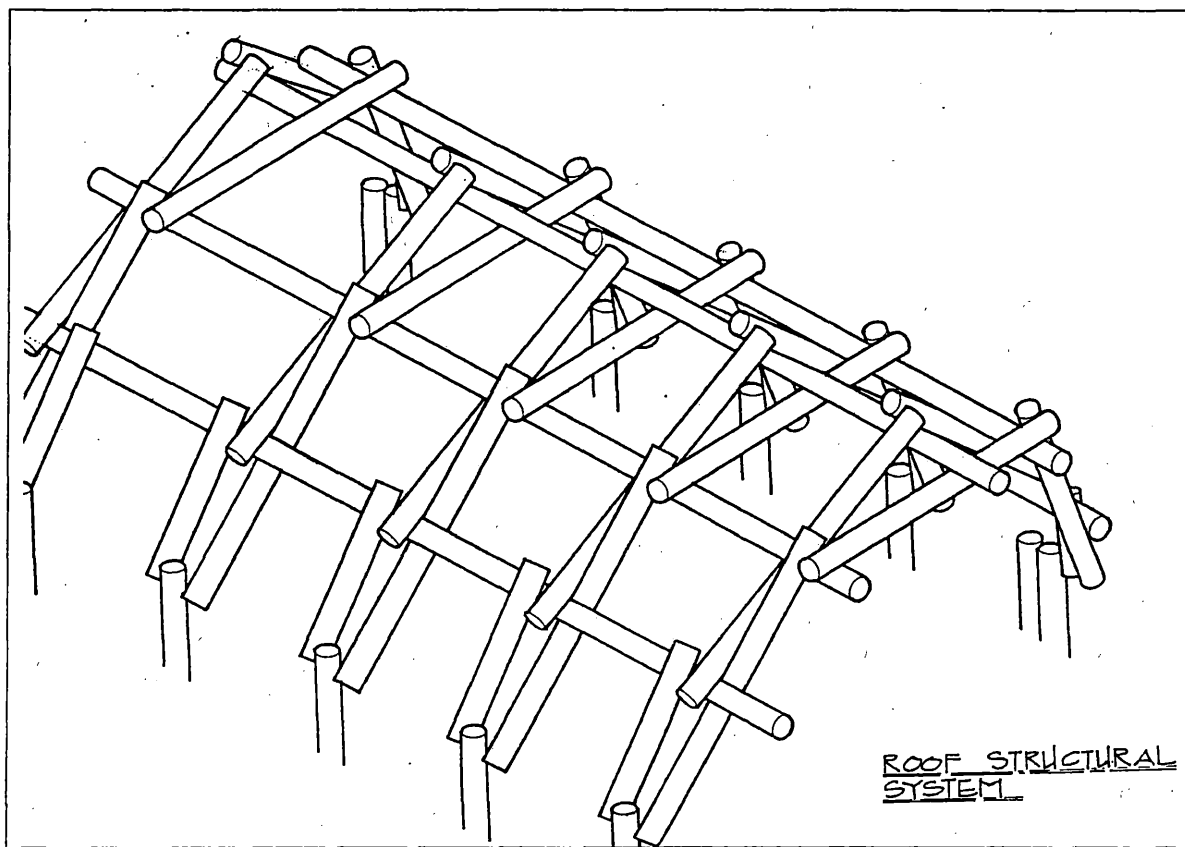
### ***Other Potential Uses***

In the past roundwood has traditionally been used for pulpwood and papermaking, flakeboard and strandboard panels, scaffolding systems, fence posts, landscaping mulch, animal bedding and fuel (Stern, 2000).

From an economic standpoint however, small roundwood logs may have a more lucrative value as building components. Round structures have significant structural advantages over square sections including strength advantages derived from grain orientation. Indeed the design load capacity of small diameter timbers could be more than five times that of the largest prismatic timber cut from them ( Wolfe, 1999). Once the material is debarked and dressed to an appropriate diameter, these materials can be used as trusses, poles, railings, and siding. Using the details outlined here, the interlaced wood arch could be used for storage structures, roof structures, domes, playground equipment, people, animal, and equipment shelters.

### **Roof Structures**

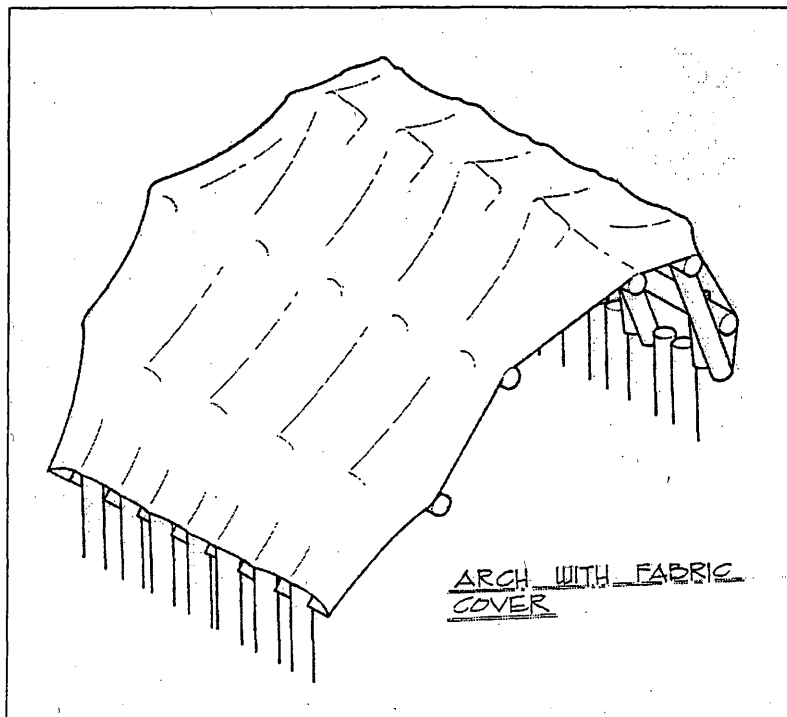
When the two ends of the interlaced arch are tied together with a tension member, the structural system acts like a truss. Trusses are useful for spanning long distances using relatively small members. In a roof assembly, trusses of three segment and four segment arches can be intertwined with cross members. The cross members can be used to carry roofing or decking eliminating the need for roof purlins. Truss spacing would be dependent upon the truss span, roundwood diameters, and roof loading.



**Figure 1.7 Interlaced Roof Structure**

### **Other Arch Structures**

Like a trussed roof assembly, the interlaced arch can also be used to create arch shelters, storage buildings, or animal shelters. When the structure is placed directly on the ground, the interlaced arches create a half cylinder that can be accessed from either end of the tube. The half cylinder can be covered with rigid decking and traditional roofing systems like asphalt shingles, rolled roofing, or metal roofing. A water proof, Teflon coated fabric could also be stretched across the structure to provide adequate shelter for people, livestock, or equipment. A translucent fabric will also provide adequate daylighting within the enclosure, eliminating the need for artificial light. These types of assemblies may be particularly useful as temporary structures.



**Figure 1.8 Roof Structure with Teflon Fabric**

## Engineering Analysis

Using the COSMOS/M structural software program, engineering students and faculty analyzed the bridge prototype. This program analyzes the internal forces, moments, stresses and deflections of structures. Two versions of the NAU Rainbow Bridge were modeled: 1) the actual bridge prototype, and 2) a version that uses a modified connection configuration. The analysts then used the allowable stress design (ASD) to study the log members and connections. ASD is widely used by structural engineers to determine the structural capability of wood structures. Finally, the engineering team developed a strength and serviceability analysis of the structure to determine how long term deterioration of the wood will affect its useful life.

Specific objectives of the engineering analysis include:

- Model current Rainbow Bridge prototype.
- Model bridge prototype with revised structural connections
- Determine the NAU Rainbow Bridge internal forces, bending moments, and deflections using the COSMOS/M Finite Element System.
- Use Allowable Stress Design (ASD) and finite element analysis (FEA) results, to arrive at the allowable loading.
- Make recommendations for possible connection designs and structural improvements.

## FINITE ELEMENT ANALYSIS (FEA)

Using the shop drawings of the Rainbow Bridge prototype, the analysts developed an as-built geometry for the structure. The bridge prototype has a span of 18 feet, and an arch height of 5 feet. This geometry formed the basis for the finite element analysis. The Rainbow Bridge prototype has three types of members:

- 1) arch members (parallel with the span of the bridge)
- 2) purlins (perpendicular to the span of the bridge)
- 3) half-inch diameter bolts (connections between arch and purlin members)

The bridge arch and purlin members were modeled using material properties for ponderosa pine.

Modulus of elasticity	$E = 1.10 \times 10^6$ psi.
Circular cross section with a radius	$r = 1.625$ in.

The following material properties were used to model the connection bolts.

Modulus of elasticity	$E = 30.0 \times 10^6$ psi.
Circular cross section with a radius	$r = 0.25$ in.

The full models consist of 3,888 elements and 3,566 nodes. Translation at the abutments was constrained in the global X, Y and Z directions for all four models. Each model was loaded with a 100-psf equivalent loading at 27 points located at exactly the same places that the decking will apply the load to the bridge prototype. The Rainbow Bridge loading requirements were developed using Uniform Building Code (UBC, 1997) specifications. The Uniform Building Code is a nationally accepted tool adopted by many city-building departments including Flagstaff, Arizona. The Uniform Building Code table 16-A specifies a 100-psf uniform live load for a pedestrian bridge.

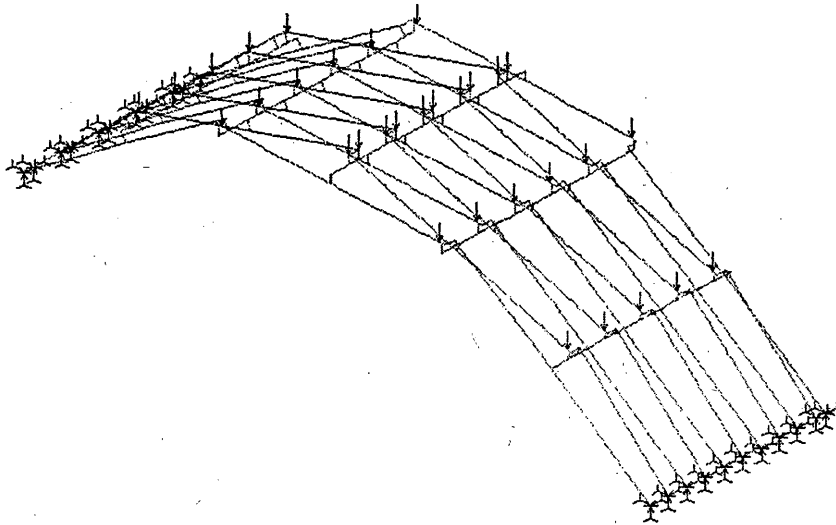
## Analysis of Test Models

Due to the different material properties of wood and steel, combining the two into one connection can cause deformation in the softer wood member. The deformation in the wood member loosens the connection and over time diminishes the connections' ability to carry bending moment. As a result, a wood structure often loses its rigidity over the course of time, and this lack of rigidity can significantly affect the structural performance of the assembly.

To study these effects, several computer models were developed. In terms of the rigidity of their connections, these models varied from rigid to flexible. After analyzing fifteen variations, the engineering team determined that five bridge modeling configurations would provide reasonably accurate results. Figure 1.9 provides a graphic representation of the full model, including loading points.

- **Full\_Model\_PurlinsB:** torsional and bending moments are released about the out-of-plane axis at the purlin end of the connectors
- **Full\_Model\_PurlinsC:** torsional and bending moments are released about both the out-of-plane axis and the in-plane axis perpendicular to the connector at the purlin end of the connectors.
- **Full\_Model\_ArchesB:** torsional and bending moments are released about the out-of-plane axis at the arch end of the connectors

- **Full\_Model\_ArchesC:** torsional and bending moments are released about the out-of-plane axis and the in-plane axis perpendicular to the connector at the arch end of the connectors
- **Full\_Model\_Archesconct:** (shown Fig 3.4) Unlike the prototype, this model uses an additional bolt to tie each arch segment together. Early analysis of the prototype indicated that the bridge could be significantly strengthened if each of the arch segments were tied together. Here, torsional and bending moments are released about both the element S-axis and the element T-axis for the arch connectors. The element S-axis and T-axis for the arch connectors lie within the plane of the bridge.



**Figure 1.9 FEA Computer Model of the Bridge Prototype**

### Finite Element Analysis Results

The five full FEA models revealed that the maximum bending stress in the bridge prototype is found at the center of the the horizontal segment of the three segment arch. The maximum shear stress occurred where the decking load is applied to the first purlin. The maximum compression stress perpendicular to the grain occurs where the arch segments bear on. The maximum deflection occurs at the center of the bridge.

Table 3.1 compares two of the models, Full\_Model\_Purlins and Full\_Model\_Archesconct. The first value given in Table 3.1 is the maximum value for the test model , while the second value signifies the node or location on the model.

Test Model	Resultant Displacement (in)/Node	X-Displacement (in)/Node	Y-Displacement (in)/Node	Z-Displacement (in)/Node	
Full_Model_ PurlinsC	1.981 / 2299	-.855 / 183	-1.874 / 2929	.035 / 2301	
Full_Model_ Archesconct	2.301 / 3624	-0.413 / 3625	-.858 / 2929	2.181 / 3624	
	Axial Force (lbs)	Shear Force (lbs)	Shear Force (lbs)	Bending Moment	Bending Moment
	/Element	/Element	/Element	(in*lb)/Element	(in*lb)/ Element
		(VT)	(VS)	(MS)	(MT)
Full_Model_ PurlinsC	-1514 / 252	-1372 / 2617	-1108 / 208	4265 / 3233	9436 / 2116
Full_Model_ Archesconc	-1192 / 231	590 / 3689	520 / 495	2142 / 450	5269 / 2116

**Table 1.1 FEA Model Results**

## STRENGTH AND SERVICEABILITY ANALYSIS

Structures can fail in several ways. When a material is loaded beyond its inherent structural capability, the material can fail causing a stress failure. On the other hand, materials can also lose strength or their shape through deterioration, age and fatigue, leading to serviceability failures. To develop an understanding of the structural capability of the rainbow bridge, the engineering team performed both a strength and serviceability analysis of the bridge prototype. A comparison of the five different bridge models indicated that model Full\_Model\_Archesconct transferred structural forces most effectively. Accordingly, the engineering team used this model in its final strength and serviceability analysis.

## ASD Analysis

The strength analysis was developed using the Allowable Stress Design (ASD) method. In Allowable Stress Design, the allowable stress for a member is compared to the actual stress in that member when the structure is loaded under a code-required load (Breyer, 1997). The allowable stresses were determined using National Design Specifications (NDS) and American Standard Testing Methods (ASTM). The FEA model determined the actual stresses in the Bridge members.

To determine the allowable stress properties for small diameter ponderosa pine, research and development was required. Research led to nominal values for small diameter Ponderosa pine properties. The primary source for the nominal allowable stress properties was work completed by Fatma Coban, Jason Hale and Peter Prebus (Coban et al, 2000). The nominal property values were developed using American Standard Testing Methods (ASTM, 1992) specifications D2555, D3957, and D245-92.

Unlike steel, the development of allowable stress for wood requires several adjustment factors to account for different situations. The National Design Specifications (NDS, 1997) provided the adjustment factors

used to develop the allowable stress properties. Because the Bridge will be located outdoors, the nominal allowable stress values were adjusted for a moisture content that will exceed 19% (NDS Table 4A, 1997). The allowable stress values for small diameter Ponderosa pine that were used in the member analysis for the Bridge are as follows:

- Allowable Bending Stress:  $F_b = 977.5$  psi.
- Allowable Compressive Stress Parallel to the Grain:  $F_c = 400$  psi.
- Allowable Tensile Stress:  $F_t = 625$  psi.
- Allowable Shear Stress:  $F_v = 97$  psi.
- Allowable Compressive Stress Perpendicular to the Grain:  $F_{c\perp} = 124$  psi.

Table 1.2 compares the allowable stress to the maximum actual stress.

Mode	Maximum Actual Stress (psi)	Allowable Stress (psi)	Margin of Safety *
Bending Stress	1564	978	-0.38
Shear Stress	84	97	-0.15
Tension Stress	3	625	206.00
Compression Stress Parallel To The Grain	149	400	167.0
Compression Stress Perpendicular To The Grain	501	124	-0.75

\* Margin of Safety = (Allowable / Applied) - 1

**Table 1.2 Allowable Stress Vs. Actual Stress.**

### Bridge Connection Analysis

The connections on the Bridge were analyzed using the Yield Limit Model for Dowel Fasteners (NDS, 1997). This Technique is an engineering mechanics approach to designing mechanical fasteners in wood (Breyer, 1997). All the connections on the Bridge are dowel connections where the dowel has one shear plane. The yield limit for dowel type connections is a function of the dowel bearing strength of the members, connection geometry, and the strength of the dowel (Breyer, 1997).

### Connection Failure Modes

According to NDS, single shear plane dowel connections have six modes of failure (NDS, 1997). Each mode is analyzed separately with an NDS equation (NDS sec. 8.2, 1997), which provides a nominal design value that is then adjusted to account for bolt spacing and geometry. The lowest adjusted nominal value is then taken as the connection design value. The six modes of failure for single shear plane dowel connections are as follows (Breyer, 1997):

- Mode Im: Crushing in the main member.
- Mode Is: Crushing in the side member.
- Mode II: Rotation of fasteners.
- Mode III<sub>m</sub>: Plastic hinge and crushing in main member.
- Mode III<sub>s</sub>: Plastic hinge and crushing in side member.
- Mode IV: Two plastic hinges per shear plane (figure 4.1).

## Results of the Connection Analysis

The bridge prototype was built with four types of single shear plane dowel connections. The only difference between the four connections is the angle between the main member and side member. Table 1.3 summarizes the connection design values compared to the actual Bridge connection values. A negative margin of safety means that the actual stress is greater than the allowable stress. A positive margin of safety means that actual stress is less than the allowable stress. Mode IV (two plastic hinges forming in a bolt) is the critical mode of failure in all four connections (see figure 4.1). Joint three has the greatest margin of safety of -0.37.

Connection	Joint Angle (Degrees)	Design Value (lbs)	Actual Joint Load (lbs)	Margin of Safety *
Arch To Purlin Connection	90.0	441.3	531.9	-0.17
Arch To Arch Joint One	30.0	581.4	379.1	+0.53
Arch To Arch Joint Two	40.0	549.3	529	+0.04
Arch To Arch Joint Three	37.3	501.5	794.2	-0.37

\* Margin of Safety = (Allowable / Applied) - 1

Table 1.3 Results of the Connection Analysis

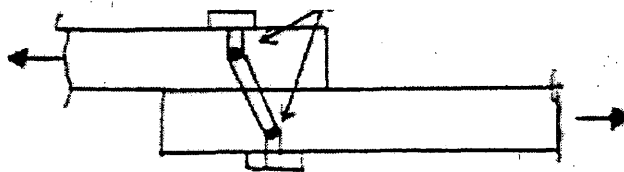


Figure 1.10 Double Plastic Hinge.

## Results of the Allowable Stress Analysis

The controlling mode of failure for the bridge prototype is compression perpendicular to the grain with a margin of safety of -0.75. The maximum compression perpendicular to the grain occurs where the arch members rest on the purlins. Compression perpendicular to the grain is a serviceability limit. The controlling stress mode of failure for the bridge is bending stress with a margin of safety of -0.38. The maximum bending stresses occur at the center of the horizontal member of the three-member arches.

## The Expected Allowable Load for the Rainbow Bridge

Assuming that the decking rails rest on all the arches of the bridge, the bridge prototype will hold 18.3-psf plus a 6.5-psf decking equaling a total allowable load of 24.8-psf. If the decking rails are not straight and only rest on two arches, the total allowable load would be reduced to 9.0-psf.

If the serviceability mode of failure is disregarded, the allowable load for the Bridge prototype would be much greater. Disregarding the serviceability mode of failure and assuming that the decking rails rest on all the bridge arches, the allowable load is 56.0-psf plus a 6.5-psf decking equaling a total allowable load of 62.5-psf. If the decking rails are not straight and only rest on two arches, the total allowable load would be reduced to 22.7-psf.

## Recommendations for Future Rainbow Bridge Designs

The bridge prototype suffers from three critical modes of failure:

- 1) The ponderosa pine material is crushed when fully loaded (compression perpendicular to grain)
- 2) The log size of 3" is not big enough to withstand the bending forces in specific members.
- 3) When fully loaded, the bolted connections can fail through double plastic hinging.

Because these problems limit the structural capacity of the bridge, future bridge designs should resolve these three critical modes of failure.

### Member Size

Increasing the member diameter and length is a consideration for future design. One of critical modes of failure for the bridge prototypes is caused by high bending stresses in the horizontal arch members.

Increasing the diameter of the members would lower the bending stresses in the members. While further modeling is needed, preliminary investigations suggest that a log diameter of 5" to 6" will meet the required code loading of 100 lbs per square foot

### Connections

Changing the connection design would improve the connection margin of safety and change the bridge's internal stresses. Currently the connections suffer from a negative margin of safety when the bridge is loaded under the UBC specified load of 100 psf. Three possible remedies for the connections are as follows:

- In lieu of the bolt connections, a steel sleeve assembly should be used. The sleeve assembly would allow the arch segments to butt together at joint intersections, changing the way the bridge members are loaded. A butted double sleeve connection would change the member loading to almost pure axial loading thus reducing the high bending stresses that occur in the current design and eliminating both the bolt bending and compression perpendicular to the grain situations. Interestingly, researchers in

Europe at Engineering Mechanics and Research Limited in Wales U.K. have developed a sleeve system for small roundwood that may be effective in interlaced arch bridges (<http://www.avalon.net/~ssi/adv.gif>). Additionally, light weight electro metallic tubing (EMT) that is used for electrical applications, could be used for low cost sleeves.

- Another solution would be to half lap and miter each log, and use a bolt to rigidly connect the two members. While this method would transfer loads effectively, it would not solve the crushing that occurs when ponderosa pine is placed under significant loading.
- Increasing the bolt diameter, using a higher-grade bolt, and/or employing a bolt sleeve would help to prevent the formation of a double plastic hinge in the arch-to-purlin connection.

## Conclusions and Recommendations for Future Work

While there are significant economic opportunities for small diameter roundwood products, there are also significant marketing challenges. Barbour et al. suggest that many innovative forest products are technically feasible, yet these products fail to reach their economic potential due to poor marketing. They concluded that the forest products industry must change from a product oriented to a market oriented philosophy. Building code officials need guidance for inspecting roundwood assemblies, and building contractors need training in how small roundwood assemblies are erected (Barbour et. al 2000).

Additionally, more work needs to be completed to assess the full potential of roundwood arch structures. The engineering analysis completed here suggests that without substantial structural improvements these arch bridges are not capable of withstanding the live and dead loads required by code. Because ponderosa pine is a soft material that deforms under load, the material will have to be strengthened with steel sleeves or gussets to prevent serviceability failures.

Additionally, more modeling must be completed to understand how the use of improved connections and larger log members affect the strength of the structure. Detailed analysis also need to be completed on the use of interlaced structures for roofs or storage structures. While these structures show promise, details will have to be developed to insure their compliance with building codes.

In conclusion, more engineering work needs to be completed in order to understand how to take full advantage of these ancient structural systems. But with improved engineering, enhanced manufacturing, and effective marketing, foresters and entrepreneurs could use these interlaced roundwood structures for multiple purposes.

## Bibliography

Altabba, B. (2000) "Re-Creating the Rainbow Bridge", Civil Engineering Magazine. May 2000

American Standard Testing Methods, (1992), specs. D2555, D3957, D245-94.

ANSI/AF&PA. National Design Specifications for Wood Construction. American Forest Paper Association, American Wood Council 1111 19<sup>th</sup> street, NW, Suite 8800 Washington, DC 20036

Barbour, R.J.; Paun, D.A; Wright, D. (In Press) Small Diameter timber: a review of the published literature. FPL-GTR-XX. Madison, WI: U.S. Department of Agriculture. Forest Service, Forest Products Laboratory.

Breyer, Fridley, Cobeen. Design of Wood Structures. New York: McGraw-Hill Inc., 1997.

Coban F, Hale J, Prebus P. Senior Design Project. Department of Civil and Environmental Engineering, Northern Arizona University, Flagstaff, AZ.: Northern Arizona University, (2000).

International Conference of Building Officials. Uniform Bldg Code. Table 16-4, VB5360 Waham Mill Rd, Whittier, CA. 90601-2298, (1997).

Stern, E.G. (2000) "Construction with Small Diameter Roundwood". Forest Products Journal. Volume 41 (4) March 2000.

Wolfe, R. (1999) "Research Challenges for Structural use of Small -Diameter Round Timbers USDA Forest Service Forest Products Laboratory, Madison: March, 1999.